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14. ABSTRACT
The past few years have seen a significant change in the roles and requirements of the U.S. Air Force. On the one hand, the well defined global threat posed by a few conventional and nuclear forces has been replaced by multiple, localized potential threats that in addition to the usual conventional and nuclear ones, also potentially involve chemical and biological weapons. In addition, the USAF role has expanded to include operations other than warfare, such as peacekeeping and humanitarian aid. Finally, limited resources mandate that these roles must he achieved in a cost-effective way.
This scenario translates into a requirement for highly versatile systems, capable of delivering near optimal performance under a wide range of conditions. In tills research we have developed a framework, based on the combination of Receding Horizon, Control Lyapunov Functions and Operator Interpolation Theory techniques, for systematically designing controllers capable of meeting these challenges. These controllers offer the following advantages over hitherto available design methods:
oThe ability to deliver near optimal performance while keeping the computational complexity compatible with an on-line implementation.

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Grant F49620–00–1–0020

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Submitted to the Dynamics and Control Program

Air Force Office of Scientific Research

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Abstract

The past few years have seen a significant change in the roles and requirements of the U.S. Air Force. On one hand, the well defined global threat posed by a few conventional and nuclear forces has been replaced by multiple, localized potential threats that in addition to the usual conventional and nuclear ones, also potentially involve chemical and biological weapons. In addition, the USAF role has expanded to include operations other than warfare, such as peacekeeping and humanitarian aid. Finally, limited resources mandate that these roles must be achieved in a cost–effective way.

This scenario translates into a requirement for highly versatile systems, capable of delivering near optimal performance under a wide range of conditions. In this research we have developed a framework, based on the combination of Receding Horizon, Control Lyapunov Functions and Operator Interpolation Theory techniques, for systematically designing controllers capable of meeting these challenges. These controllers offer the following advantages over hitherto available design methods:

- The ability to deliver near optimal performance while keeping the computational complexity compatible with an on–line implementation.
- The ability to systematically trade–off computational power versus performance.
- The ability to explicitly address the issue of multiple performance specifications and model uncertainty, identifying the limits of performance of the plant and making unavoidable design tradeoffs clear.

These advantages were validated in the problems of (a) control of thrust–vectored aircrafts, and (b) vision–based tracking of non–cooperative targets. A description of the experiments and several demos can be found at `http://robustsystems.ee.psu.edu`.

Finally, in addition to contributing to the specific mission of the USAF, the framework developed here also benefits society at large. The new controllers can result in substantially reduced operating costs in a large number of applications including commercial aircrafts, process control and internet traffic control. In addition, when combined with computer vision, the resulting robust dynamic vision systems can be used to increase security in sensitive areas, allow elderly people to continue living independently and monitor and even coordinate responses to environmental threats to minimize their effect.

Contents

1 Description of the Research Effort

1.1 Objectives:

The objective of this research effort was to develop a simple synthesis framework for nonlinear systems that explicitly takes into account multiple performance specifications, hard constraints, and model uncertainty. In this context, the following tasks were accomplished:

- Development of computationally tractable synthesis methods for nonlinear and parameter varying systems that lead to physically implementable controllers.
- Development of robust identification and model (in)validation techniques well matched to these control methods.
- Application of the resulting theory to the problems of (i) controller design for thrust vectored aircrafts and (ii) robust visual tracking of noncooperative targets.

Several video clips illustrating these results can be found at `http://robustsystems.ee.psu.edu`.

1.2 Benefits to the US Air Force

In order to successfully handle threats arising in the next decades, the Air Force will increasingly rely on a digitized battlefield, where highly versatile intelligent systems such as uninhabited combat and reconnaissance air vehicles (UCAVs and URAVs) are key players. These aircraft will be required to serve in multiple roles, across a spectrum of scenarios, often far away from their bases and in uncertain, adversarial environments.

In order to meet these objectives, future control systems will be required to deliver near–optimal performance operating under a wide range of conditions. Thus, these controllers will necessarily have to deal with the nonlinear features of the plant, arising for instance, from the nonlinear dependence of the aerodynamic coefficients on the angle of attack and Mach number, or the use of nonlinear sensors such as computer vision. However, in contrast to the case of linear systems where several optimal synthesis techniques (such as $\mathcal{H}_\infty$, $\mathcal{H}_2$ and ℓ^1) are well established, their nonlinear counterparts are just starting to emerge. Moreover, recent counterexamples illustrate the fact that the resulting closed–loop performance is highly problem dependent.

This research has taken steps towards removing these limitations by developing a new class of near–optimal controllers for control–affine nonlinear systems These controllers offer the following advantages over hitherto available design methods:

- The ability to deliver near optimal performance while keeping the computational complexity compatible with an on–line implementation.
- A design paradigm that can systematically trade–off computational power versus performance.
- The ability to explicitly address the issue of multiple performance specifications and model uncertainty, identifying the limits of performance of the plant and making unavoidable design tradeoffs clear.

These advantages were experimentally validated in the problem of vision–based tracking of non–cooperative targets. Controlled dynamic vision is now positioned in an optimal situation to address the challenges arising in the context of endowing UCAVs and URAVs with the capabilities required to serve across a wide spectrum of missions, provided that adequate robustness can be incorporated into the resulting systems to allow

for successful operation in highly uncertain scenarios. Proof–of–concept experimental systems developed under this grant show that this can be accomplished by exploiting the control techniques developed here.

1.3 Benefits to the Public:

The controllers developed under this grant have the potential to deliver near optimal performance under a wide range of conditions. Thus, they can result in substantially reduced operating costs in a large number of applications including commercial aircrafts, process control and internet traffic control. In addition, when combined with computer vision, the resulting robust dynamic vision systems can be used to increase security in sensitive areas, allow elderly people to continue living independently and monitor and even coordinate responses to environmental threats to minimize their effect.

2 Technical Results

2.1 Summary of the results

This research was carried out using a combination of Control Lyapunov Functions, Receding Horizon and Interpolation Theory tools. This combination led to the following results:

Theoretical:

- Combination of Control Lyapunov Functions (CLF) and Receding Horizon techniques to obtain controllers guaranteed to outperform those obtained using CLF methods alone [2,10,17,20,24] [1].
- Development of a robust $\mathcal{H}_2$ control framework for constrained systems [3,4,8,9].
- Development of Control Oriented Identification and Model (In)validation methods for parameter-varying, not necessarily $\mathcal{L}_2$ stable systems [6,11,12,16].
- Development of risk–adjusted robust control methods for arbitrary uncertainty structures [13,15,25,42].

Applications:

- Validation of the theoretical framework in the problems of control of a simplified thrust vectored aircraft [2,17], visual tracking of uncooperative targets [7,14,18,21,29,33,37,39] and activity recognition [30].

2.2 Technical Details:

The technical details of the approach are summarized in the sequel. For the sake of brevity, only the key points are listed here. Complete details can be found in the corresponding publications.

• Nonlinear Control via Receding Horizon Constrained Control Lyapunov Functions.

Consider the control affine nonlinear system:

$$\dot{x} = f(x) + g(x)u, \qquad u \in \Omega_u \tag{1}$$

where the convex set Ω_u represents hard constraints on the control action. The goal is to find a feedback

[1] These numbers are keyed to the publications list in section 5

control law $u[x(t)]$ that minimizes the following performance index:

$$J(x_o, u) = \frac{1}{2} \int_0^\infty [x'Q(x)x + u'R(x)u] \, dt, \; x(0) = x_o \tag{2}$$

It is well known that the problem above is equivalent to solving a Hamilton–Jacobi–Bellman partial differential equation. Unfortunately, the complexity of this equation prevents its solution except in some very simple, low dimensional cases. To handle this difficulty, we have developed a controller based upon the combination of Receding Horizon and CLF techniques [2,10,17]. The central idea of the approach is to recast the nonlinear problem as the following equivalent *finite-horizon* optimization problem:

$$u_\Psi(t) = \operatorname*{argmin}_{u \in \Omega_u} \quad \left\{ \tfrac{1}{2} \int_t^{t+T} (x'Qx + u'Ru) \; dt + \Psi[x(t+T)] \right\} \tag{3}$$

where $\Psi(.)$ is a Constrained Control Lyapunov Function (CCLF) for system (1) in the sense that it is radially unbounded in x and

$$\inf_{u \in \Omega_u} \left[\frac{\partial V}{\partial x} f(x) + \frac{\partial V}{\partial x} g(x) u \right] < 0, \qquad \forall \, x \neq 0 \tag{4}$$

When solved on-line this optimization problem leads to a Receding Horizon type control law with the following properties:

1. It renders the origin an asymptotically stable equilibrium point of (1) in the entire region where the system is stabilizable with a bounded control action.
2. Coincides with the globally optimal control law when $\Psi(x) = V(x)$, the actual (local) storage function.
3. Its suboptimality level decreases monotonically along the trajectories of the system (i.e it is guaranteed to move the system in the "right direction").

• **Construction of non–conservative CCLFs**

In principle, a simple way of finding a CCLF is to find first a CLF using any of the methods available in the literature, such as feedback linearization and backstepping and then considering an invariant set S_c where the associated control action does not exceed the bounds. However, this approach may require the use of an impractically large horizon T in the optimization to guarantee that the set S_c is reached. As part of this research we have developed a method to generate CCLFs, based upon the combination of state dependent coefficient representations (SDC) and state dependent scalings. An outline of this approach is given in the sequel. Full details can be found in [10,17].

Begin by rewriting the nonlinear system (1) into the following linear–like form:

$$\dot{x} = A(x)x + B(x)u \tag{5}$$

and assume that, for every x the pair $[A(x), B(x)]$ is stabilizable (in the linear sense). Consider now the following Riccati equation, parametric in x and τ:

$$0 = A'(x)P(x,\tau) + P(x,\tau)A(x) + \frac{1}{\tau}Q(x) - P(x,\tau)B(x)B'(x)P(x,\tau) \tag{6}$$

and the associated control law:

$$u = -B'P(x,\tau)x \tag{7}$$

where $P(x,\tau)$ is the positive definite solution of (6). Finally, given a compact domain $\mathcal{D} \subset R^n$, consider the mapping $\tau : \mathcal{D} \to R^+$ defined implicitly by the solution to the following equation:

$$\alpha(\tau)x'P(x,\tau)x = 1 \tag{8}$$

where

$$\alpha(\tau) = \max_i \left\{ \max_{x\in\mathcal{D}} \left\{ \frac{b_i(x)'P(x,\tau)b_i(x)}{u_{max}^2} \right\} \right\} \tag{9}$$

Note that $\hat{P}(x) \doteq P(x,1)$ is precisely the solution to the SDRE associated with the system (5) and hence is a CLF in a neighborhood $\mathcal{N}$ of the origin. Let $S_{\mathcal{N}} \subseteq \mathcal{N}$ be a controlled–invariant set with respect to the control law[2]:

$$\hat{u} = -B(x)'\hat{P}(x)x \tag{10}$$

and define the sets:

$$\begin{aligned} \mathcal{E} &= \left\{ x : x'\hat{P}(x)x \leq \tfrac{1}{\alpha(1)} \right\} \\ S_1 &= \mathcal{E} \cap S_{\mathcal{N}} \end{aligned} \tag{11}$$

Theorem 1 *Given a compact region $\mathcal{D} \subseteq R^n$, assume that there exist some $\tau_{max} > 1$ such that*[3]

$$\mathcal{D} \subseteq S_{\tau_{max}} \left\{ x : x'P(x,\tau_{max})x \leq \alpha(\tau_{max})^{-1} \right\}$$

If, for every fixed $\tau \in [1,\tau_{max}]$ the function $\phi(x,\tau) = x'P(x,\tau)x$ is a CLF with respect to the control action $u_\tau = -B'P(x,\tau)x$, then

$$\Psi(x) = \begin{cases} \frac{1}{2}x'P\left[x,\tau(x)\right]x & x \in S_{\mathcal{N}}/S_1 \\ \frac{1}{2}x'P\left[x,1\right]x & x \in S_1 \end{cases} \tag{12}$$

is a CCLF for (1) in the region $\mathcal{D}$.

• Control Oriented Identification and Model (In)Validation.

In parallel with the controller design effort, we extended the worst–case identification/model (in)validation framework developed in the early to mid 1990's to the case of Linear Parameter Varying, not necessarily stable, plants. Our main result shows that in these cases generalized interpolation theory can be used to recast the problem into an LMI form. The overall complexity of the resulting algorithm is similar to that of identifying and validating LTI systems of comparable size. In addition we have extended these techniques to the case where the plant is not necessarily open loop $\mathcal{L}_2$ stable. This is of particular importance for applications such as visual tracking and activity recognition (see [11,12,39] for details). Finally, we have obtained necessary and sufficient convex conditions for model invalidation in the presence of arbitrarily slowly time–varying structured uncertainty. Using these conditions entails a substantial complexity conditions over currently available methods, since these are known to lead to NP–hard problems whose computational complexity scales exponentially with the number of uncertainty blocks.

[2]Such a set can be constructed for instance by finding $c \doteq \inf_{x\in\partial\mathcal{N}} x'\hat{P}x$ and defining $S_{\mathcal{N}} \doteq \left\{ x : x'\hat{P}x \leq c \right\}$.

[3]It can be shown that if $A(x)$ is pointwise Hurwitz then $S_{\tau_{max}} = R^n$.

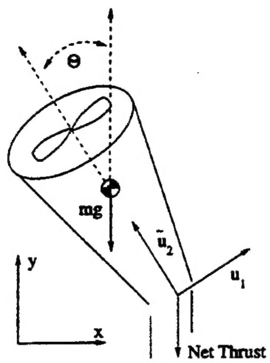
2.3 Applications:

The theoretical framework developed under this grant has been validated in the following applications:

(a) The Ducted Fan: Consider the planar ducted fan shown in Figure 1(a), (a simplified model of a thrust vectored aircraft) with dynamics given by:

$$\begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} -g sin\theta \\ g\,(cos\theta - 1) \\ 0 \end{bmatrix} + \begin{bmatrix} \frac{cos\theta}{m} & -\frac{sin\theta}{m} \\ \frac{sin\theta}{m} & \frac{cos\theta}{m} \\ \frac{r}{J} & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{13}$$

where x, y and θ denote horizontal, vertical and angular position respectively and where u_1 and u_2 are the control inputs.



Method	Cost
LQR	1.1×10^5
CLF	2.53×10^4
LPV	1833
SDRE	1989
Optimal (off line)	1115
New	**1117**

Figure 1: (a) Simplified model of a thrust vectored aircraft. (b) Performance of different controllers.

The goal is to minimize a performance index of the form (2) with:

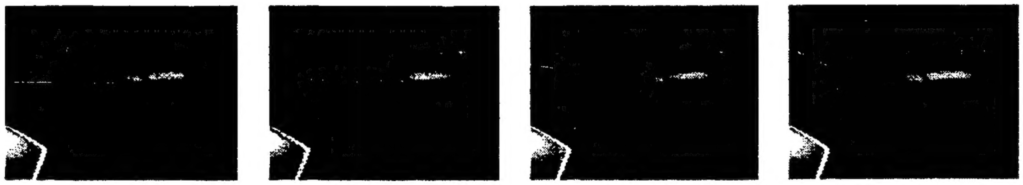
$$Q = diag\,[5 \quad 5 \quad 1 \quad 1 \quad 1 \quad 5]\,,\; R = I_{2\times 2}$$

corresponding to the following choice of state variables: $\xi = [x \quad y \quad \theta \quad \dot{x} \quad \dot{y} \quad \dot{\theta}]$. Figure 1(b) shows the performance achieved by several controllers, starting from the initial condition $\xi(0) = [0 \quad 0 \quad 0 \quad 12.5 \quad 0 \quad 0]$. Note that the proposed approach (RHCCLF) outperforms all other techniques, achieving a cost virtually equal to the global optimum.

(b) Robust active tracking of non-cooperative targets in uncertain environments: Currently available UAVs, equipped with appropriate sensors and decision capabilities, can carry out a wide spectrum of missions, including intelligence gathering, target search and identification, and activity analysis. All of these applications require having robust active vision systems, capable of operating in adversarial, highly uncertain environments, and endowed with the ability to (i) *track* the target(s), (ii) zoom in features of interest, and (iii) *recognize the actions* being undertaken. As we briefly illustrate next, tools developed under this grant can effectively accomplish this.

(i) Object Localization and Tracking: In principle, the location of the target can be predicted using a combination of the target dynamics, empirically learned noise distributions and past position. However, this process is far from trivial in a cluttered environment.

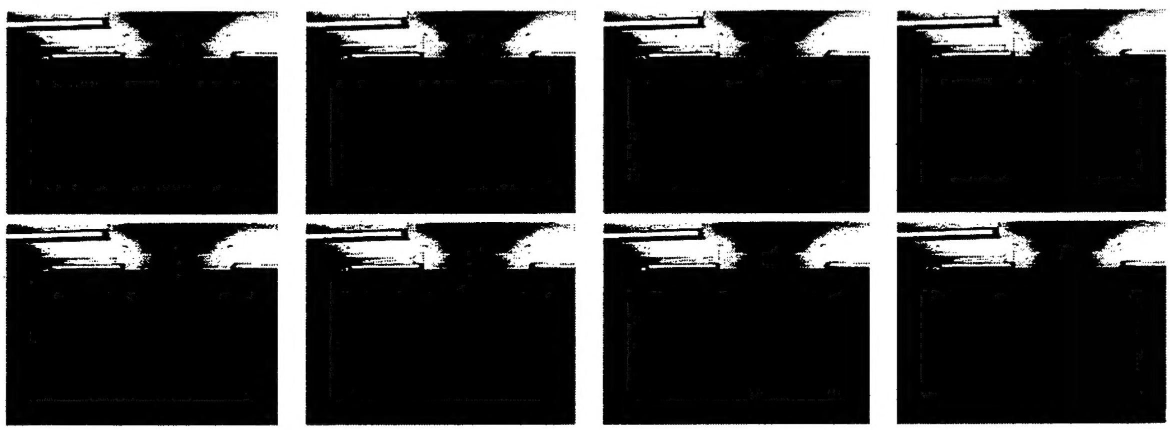
Figure 2 shows the results of using a Mean Shift based tracking (white crosses) implemented in Intel's Open Source Computer Vision Library. Although this algorithm is designed to improve tracking robustness by exploiting color information, it begins to track poorly in frame 19, and by frame 21 it has completely lost



Frame 8 Frame 14 Frame 19 Frame 21

Figure 2: Robust identification based tracking (black cross) versus Mean Shift (white cross)

the target due to a combination of clutter and moderate occlusion. This difficulty can be solved by modelling the motion of the target as the impulse response of an unknown non Schur plant, and using our theory to identify the relevant dynamics. The advantage of this approach is illustrated in Figure 2, where the black crosses indicate the position of the centroid predicted by our model. As shown there, the identified model is able to correctly predict the location of the target, far beyond the point where the Mean Shift tracker has failed.



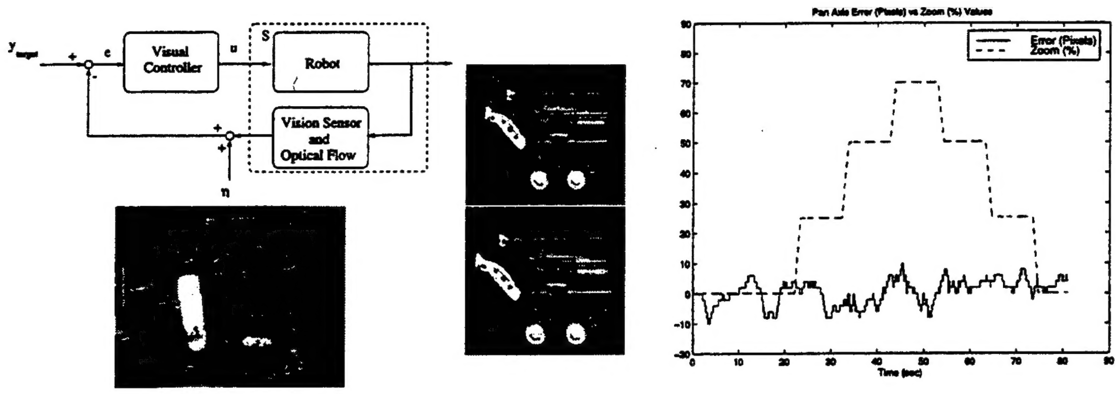
Frame 150 Frame 105 Frame 95 Frame 85

Figure 3: Two examples of a combination Kalman and Operator based tracking in the presence of occlusion

Finally, as shown in Figure 3, the proposed approach can be used to substantially improve robusteness of trackers, such as Kalman and Unscented Particle Filters, that rely on a combination of past measurements and the dynamics of the target to estimate its future location. As shown there, this approach is able to handle both casual (top) and malicious (bottom) occlusion. Moreover, this performance improvement is achieved *together* with a substantial *computational complexity reduction*, since the combination Kalman–Filter/Operator-based interpolator significantly outperforms an Unscented Particle Filter that requires considerably more on–line computations.

(ii) Visual Servoing: Once the target has been localized, the next task that needs to be accomplished is to hold the gaze at distinguished features of the target, by actively controlling the cameras and zooming into features of interest. Our framework allows for robustly accomplishing this by using a combination of robust identification and model (in)validation techniques to obtain an LPV model of the plant, and the associated uncertainty description. In turn, these can be combined with the controller synthesis framework to obtain a robust LPV controller. Figure 4 shows the results of an experiment where a non–cooperative target is

tracked while zooming in an out of its features. As shown in Figure 4(b) the controller achieves good tracking performance, in spite of the substantial change in the dynamics of the system due to the zooming action, and the presence of clutter.



(a) (b) (c)

Figure 4: (a) A visual tracking system. (b) Target for different values of f. (c) Tracking error while zooming.

(iii) Activity Recognition: Once the target has been tracked for an adequate amount of time, the data collected can be used to analyze its activity. We have shown that this problem can be solved by using interpolation theory tools to recast it as the combined identification/model (in)validation of a marginally stable system (see [30] for details).

3 Personnel Supported:

- Mario Sznaier (PI).
- Ms. Cecilia Mazzaro, Ph.D. Candidate.
- Mr. Brian Murphy, Ph.D. Candidate.

4 Interaction with AFRL

Part of this research was conducted in collaboration with Dr. Jim Cloutier, AFRL Navigation and Control Branch, Eglin AFB (now retired).

5 Publications:

Journal

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2. M. Sznaier, J. Cloutier, R. Hull, D. Jacques and C. Mracek, *"A Receding Horizon State Dependent Riccati Equation Approach to Suboptimal Regulation of Nonlinear Systems,"* AIAA J. Guidance and Control, 23, 3, pp. 399–405, 2000.

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Book Chapters

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